USAF SPACE SENSING CRYOGENIC CONSIDERATIONS

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14. ABSTRACT
Infrared (IR) space sensing missions of the future depend upon low mass components and highly capable imaging technologies. Limitations in visible imaging due to the earth?s shadow drive the use of IR surveillance methods for a wide variety of applications for Intelligence, Surveillance, and Reconnaissance (ISR), Ballistic Missile Defense (BMD) applications, and almost certainly in Space Situational Awareness (SSA) and Operationally Responsive Space (ORS) missions. Utilization of IR sensors greatly expands and improves mission capabilities including target and target behavioral discrimination. Background IR emissions and electronic noise that is inherently present in Focal Plane Arrays (FPAs) and surveillance optics bench designs prevents their use unless they are cooled to cryogenic temperatures. This paper describes the role of cryogenic coolers as an enabling technology for generic ISR and BMD missions and provides ISR and BMD mission and requirement planners with a brief glimpse of this critical technology implementation potential. The interaction between cryogenic refrigeration component performance and the IR sensor optics and FPA can be seen as not only mission enabling but also as mission performance enhancing when the refrigeration system is considered as part of an overall optimization problem.

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USAF SPACE SENSING CRYOGENIC CONSIDERATIONS

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ABSTRACT

Infrared (IR) space sensing missions of the future depend upon low mass components and highly capable imaging technologies. Limitations in visible imaging due to the earth's shadow drive the use of IR surveillance methods for a wide variety of applications for Intelligence, Surveillance, and Reconnaissance (ISR), Ballistic Missile Defense (BMD) applications, and almost certainly in Space Situational Awareness (SSA) and Operationally Responsive Space (ORS) missions. Utilization of IR sensors greatly expands and improves mission capabilities including target and target behavioral discrimination. Background IR emissions and electronic noise that is inherently present in Focal Plane Arrays (FPAs) and surveillance optics bench designs prevents their use unless they are cooled to cryogenic temperatures. This paper describes the role of cryogenic coolers as an enabling technology for generic ISR and BMD missions and provides ISR and BMD mission and requirement planners with a brief glimpse of this critical technology implementation potential. The interaction between cryogenic refrigeration component performance and the IR sensor optics and FPA can be seen as not only mission enabling but also as mission performance enhancing when the refrigeration system is considered as part of an overall optimization problem.

INTRODUCTION

The use of cryogenics in space sensing technologies is the application of both active and passive cooling to enable the performance of electronic sensing components. The most obvious of these are IR detectors which have been tied to cryogenics for the past six decades [1]. But this is only one component of several to be found in space borne sensors. Superconducting electronics, optics, and other components may require cryogenic temperatures for operation. Traditional cooling methods include the use of cryostats, space radiators, and the different forms of compressor and pump types of coolers. Component insulation, heat transport, and spacecraft heat rejection are also crucial to effective space sensing operation. The US Air Force Research Laboratory (AFRL), Space Vehicles

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Directorate (RV) is the center for USAF space cryogenic and thermal research and development. The most notable current interests are technology development for SSA, missile launch detection, ORS, and ISR missions.

SPACE SENSING THERMAL NEEDS

The long standing technology requirements in this area have been for USAF ISR missions which utilize IR devices. A discussion of applicable IR wavelengths and detector materials will be given in the "Detector Thermal Interactions" section.

Missile Launch Detection

The large scale, Defense Support Program (DSP), was first launched in 1970 as a worldwide missile launch detection system and included IR detectors, FIGURE 1. The USAF is actively pursuing a DSP satellite replacement that includes active IR cooling. Due to the relatively low altitude of these targets (endo-atmospheric) and atmospheric considerations, the most effective IR wavelength for detection and track is short wave to mid wave IR (MWIR). This is graphically illustrated as FIGURE 2. The cryocoolers for this mission must be long life (>10years), operate at approximately 110 K, and have low vibration levels (on the order of <5 mN).

Figure 1. DSP Satellite

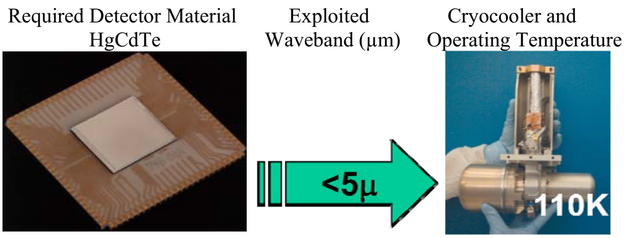

Figure 2. MWIR missile launch detection components

Midcourse Missile Tracking

Ballistic missile midcourse is the flight phase after boost and prior to atmospheric reentry. Again, this is a long standing interest of the USAF and the MDA and holds many technological challenges. From a sensor based perspective this includes the detector array as well as the necessary cryogenic cooling. Unlike the boost phase, missile warheads have separated from their hot missile bodies and radiate much less IR; FIGURE 3.

This can be compounded by countermeasures that may be used to cool the ballistic warhead. Two detector and thermal approaches are shown in FIGURE 4 and FIGURE 5.

FIGURE 4 illustrates a detector and cryocooler combination capable of detection and track of missile warheads in the Long Wave IR band (<14 μm). This approach has received serious attention and funding both in the cryocooler unit itself as well as peripheral components to improve its operation. The focal plane array (FPA), which is a matrix of mercury cadmium and tellurium alloy detectors, must be cooled to approximately 35 K. FIGURE 4 shows such a cooler with two cold heads: one at 35 K to cool the FPA, and one at 85 K to cool the telescope optics. FIGURE 5 illustrates a FPA and cryocooler combination exploiting the very long-wave IR for increasing the detection and track of cold to very cold midcourse ballistic warheads.

Figure 3. Midcourse warhead

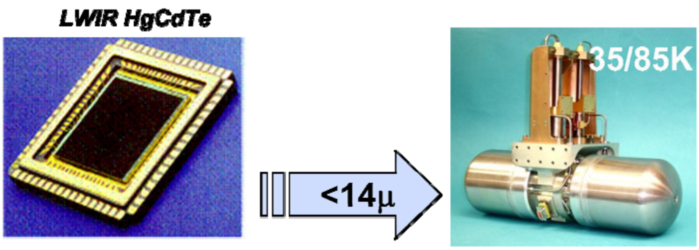

Figure 4. LWIR midcourse tracking components

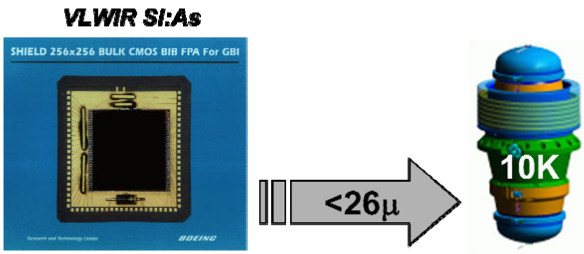

Figure 5. VLWIR midcourse tracking components

Space Situational Awareness

The USAF has been concerned and active in the tracking of active and inactive satellites and space debris since the late 1950's. Many ground based systems have been developed, deployed and are operational, but today it is clear that space based surveillance systems are required to meet more challenging mission demands. In addition to active research to identify missions and associated technologies in this area, the USAF is continuing its Space Based Surveillance System (SBSS). SBSS (FIGURE 6) will be an SSA asset with a visible sensor but may in the future contain IR capability.

Operationally Responsive Space (ORS)

The overall ORS approach is to expedite development and fielding of select responsive space systems. ORS will use the most expeditious requirements, resource allocation and acquisition processes available as appropriate to the urgency of each need. This philosophy extends to all technology developments that will aide in meeting these goals including space sensors.

DETECTOR THERMAL RELATIONSHIPS

Proper thermal integration of IR sensor components, especially for the detectors or FPA, is crucial. The principal missions and operating wavelengths have been mentioned previously. There are several types of IR detectors, many of which are experimental or not of sufficient sensitivity for the before mentioned missions [2]. Examples include Quantum Well IR Photodetectors (QWIP), nanotubes, and quantum dots. This discussion will focus upon a relative few that have been qualified for detecting targets of military interest; see FIGURE 7 and TABLE 1.

Figure 6. SBSS artist rendition

Table 1. Performance metrics of selected FPA materials

Material	Spectral band (micron)	Operating temperature (K)
Si	<1	300
PtSi	1-5	60-90
InSb	<6	35-90
PbSe	1-5	220
HgCdTe SWIR	<3	150-220
HgCdTe MWIR	2-6	100-120
HgCdTe LWIR (low background)	6-14	35-40
Si:As	6-28	8-12
QWIPs	various l micron bands	40-80
PbS	1-3	220-300

The three listed detector materials in FIGURE 7 are Mercury-Cadmium-Tellurium (HgCdTe), Blocked Impurity Band Arsenic doped Silicon (Si:As BIB), and QWIPs. The plots of quantum efficiencies against the four post boost missile representative blackbody curves reveals the obvious contenders for the space-borne USAF missions in the wavelength bands of <5μm, and <26 μm based on sensitivity alone. TABLE 1 lists these detector materials, their operating spectral band and operating temperatures. Also listed are other material types that are less commonly used for USAF missions. These detector materials have wide use in avionic and terrestrial application, or have been used in the past in space. Today most space applications use silicon in the visible band, various alloy compositions of HgCdTe in the SWIR through LWIR bands, or Si:As for the VLWIR band. Increased interest in various wide-field, scanning applications is based upon the availability of InSb and HgCdTe in array sizes of over 4 million pixels operating in the SWIR and MWIR bands. For system operation detectors must be cooled below their maximum operating temperature, as indicated in TABLE 1. Second, the operating noise of the detector itself must be reduced to a fraction of the array's dynamic output, usually below a figure of one sixth of the anticipated output of the detector when it is viewing an average target. This operating noise comes from several sources in the detector, many thermally induced, and is called "dark current." Detector cooling also enables the use of a wider-band or more capable FPAs.

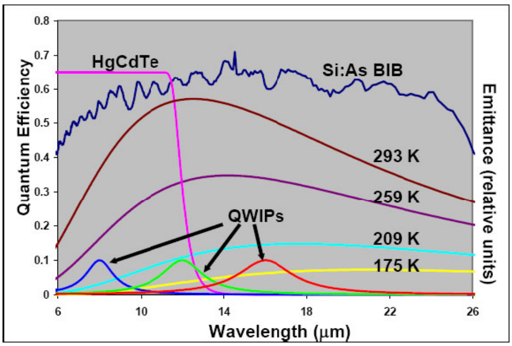

Figure 7. Performance curves of Selected FPA Materials

CRYOGENIC REFRIGERATION'S ROLE IN DETECTOR OPERATION

Aside from the near impossibility of detecting the IR signature of something that is colder than the detector, active refrigeration becomes critical to mission success for several reasons. As mentioned above, certain materials simply don't function above critical temperatures. In order to see distant and dim targets, even visible or ultraviolet light detectors may have to be cooled in order to increase their signal-to-noise ratio. This issue does not apply in the background-limited case (as the background noise predominates over the detector noise), but in the case of SSA in which distant moving objects do not have bright backgrounds, greater cooling loads and lower temperatures are beneficial.

CRYOCOOLER EFFICIENCY IMPROVEMENTS

As cryocooler efficiency improves there is a "trickle down" effect on the reduction of satellite required power and satellite mass. This is because of the decreased size requirement of the solar panels, space radiator, and thermal transport components. To illustrate this FIGURE 8 describes a fictitious smallsat system requiring 10 K operation and a mass boundary between 400 to 500 kg [3]. This mission is enabled by improvements in cryocooler improvements. Efficiency gains are still a focus of AFRL R&D due to the power and mass reductions; a critical factor in the space environment. FIGURE 9 illustrates the active refrigeration efficiency trends since 2002 and plots them against the AFRL goals for 2020 [3].

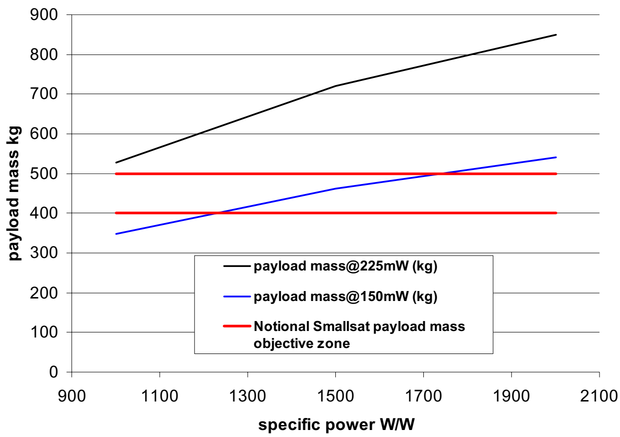

Figure 8. 10 K Cryocooler on notional smallsat

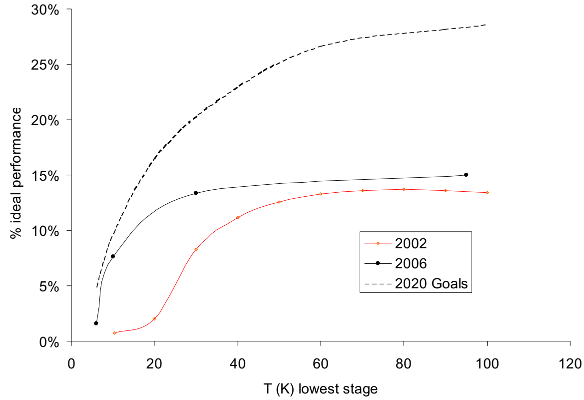

Figure 9: Active refrigeration efficiency trends

CRYOCOOLER JITTER

AFRL has identified jitter reduction to be of growing importance due to increased performance that would result with imaging and near imaging systems. One clear example is with missile warning detection and track where vibration levels well below 5 mN are required.

GOALS AND R&D TO ADDRESS NEEDS

To meet USAF IR space sensing needs AFRL has identified several goals for R&D. It is clear that sterling and pulse tube efficiency gains will reduce power and mass. Off gimbal advances will reduce induced jitter, overall spacecraft power and mass. Improved thermal designs will also have the same crucial effect of reducing power and mass. TABLE 2 details the overall performance goals set by AFRL

Table 2. Key AFRL Cryocooler Performance Metrics

KEY PERFORMANCE METRICS	GOALS		
Cold Head Temp.	60 K	35 K	10 K
Power Efficiency	15 W/W	38 W/W	250 W/W
Long Term Reliability		≥10 year	
Vibration Level (total)		≤5 mN	

SUMMARY

AFRL is active in pursuing improvement to cryogenic components for various spacecraft surveillance missions including missile launch detection, midcourse tracking, space situational awareness, and operationally responsive space. A brief description was given for the need of cryogenic operation in IR space surveillance. The most prevalent need is to cool the IR detectors below that of the observed field of view. It is also important to

cool these detectors because of their inherent internal noise. Often it is necessary to cool the optics assembly to reduce self emissions that would raise the FPA noise floor. Several of our goals have been listed in the text including: active refrigeration efficiency gains, power and mass reduction, and inducted jitter reduction.

Small businesses play an important role in this technology development. The US government Small Business Innovative Research offices are very active. These include the MDA, the USAF, and NASA. The best R&D scenario, and the SBIR award that has the highest probability, is for small businesses to team with large cryocooler producers.

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